

# **Laboratory Benchmarks for the Development of Numerical Ocean Models**

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Award Number: N000140110297

## **LONG-TERM GOAL**

The long-term goal of this project is to assess the feasibility of using laboratory models of turbulent coastal flows to develop improved parameterizations for oceanic boundary turbulence, thus contributing to the improvement of predictive coastal ocean models.

## **SCIENTIFIC OBJECTIVES**

The scientific objective of this research is to understand the impact of boundary turbulence on coastal circulation in the absence and presence of topographic features such as submarine canyons. The near-term objectives include: (i) to check experimentally if boundary turbulence, at values of the system parameters relevant to the coastal oceans, alters the velocity and density fields; (ii) to obtain a better understanding of turbulent boundary layers associated with currents along sloping surfaces in rotating stratified flows; (iii) to utilize laboratory data to parameterize the effects of boundary turbulence on the large-scale flows; and (iv) to determine the vertical basin-scale diffusivity of buoyancy for smooth and rough topographies, both with and without a submarine canyon.

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>30 SEP 2001</b>		2. REPORT TYPE		3. DATES COVERED	
4. TITLE AND SUBTITLE <b>Laboratory Benchmarks for the Development of Numerical Ocean Models</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Institute of Marine and Coastal Sciences,,Rutgers University,,New Brunswick,,NJ, 08901</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited.</b>					
13. SUPPLEMENTARY NOTES <b>The original document contains color images.</b>					
14. ABSTRACT <b>The long-term goal of this project is to assess the feasibility of using laboratory models of turbulent coastal flows to develop improved parameterizations for oceanic boundary turbulence, thus contributing to the improvement of predictive coastal ocean models.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES <b>7</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

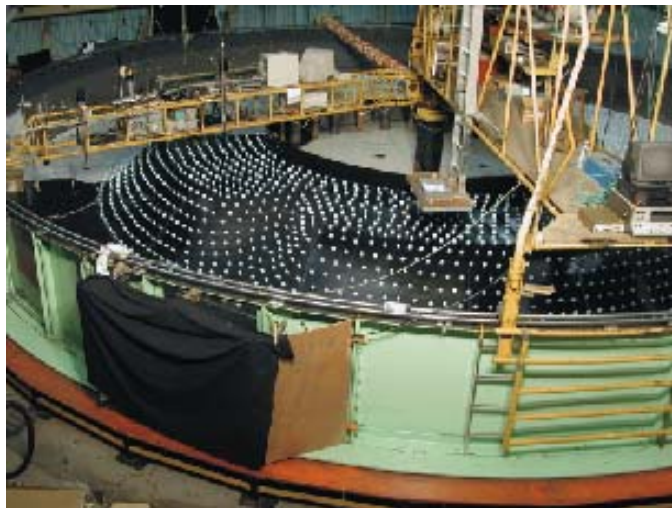
## APPROACHES

The laboratory experiments were conducted on the Coriolis rotating platform in Grenoble, France. The rotating platform is 14 m in diameter (see figure 1), and a circular fiberglass tank of diameter  $D_T=13$  m was used as a test cell. Topographic models of the shelf, shelf break and continental slope -- both without a canyon and interrupted by a single canyon -- were placed in the center of the test cell. In some experiments, the entire shelf, shelf break and continental slope (including the canyon area) were covered by cubic roughness elements (of size  $d=3$  cm). We considered flows produced by oscillatory forcing and by impulsive forcing. The flow characteristics are measured using conductivity probes, acoustic Doppler velocimetry and correlation image velocimetry (CIV). In addition to these measurements, particle streaks and dye tracers were successfully employed.

The accompanying numerical simulations thus far conducted at IMCS have utilized two different models -- the Spectral Element Ocean Model (SEOM), and the Regional Ocean Modeling System (ROMS). The two models differ primarily in their respective approaches to spatial discretization (high-order finite element and low-order finite difference respectively), but are terrain-following so that in principle both should offer convergent solutions to flow problems featuring strong topographic variations and stratification. Haidvogel and Beckmann (1999) give a concise description of both model classes.

## WORK COMPLETED

This work is a continuation of our previous studies (Perenne *et al.* 2001a, 2001b) where as a first step laboratory experiments were conducted on a small rotating platform at Arizona State University in which case laminar flow produced by oscillatory or impulsive forcing was introduced over topography interrupted by a canyon.



*Figure 1. Experimental facility.*

	Oscillatory forcing $P_1$	Oscillatory forcing $P_2$	Impulsive forcing (upwelling favorable flow) $P_3$	Impulsive forcing (downwelling favorable flow) $P_4$
Ro	0.1	0.14	0.16	0.16
Ro <sub>t</sub>	0.52	0.50		
Ek	$3 \times 10^{-4}$	$1 \times 10^{-4}$	$1 \times 10^{-4}$	$1 \times 10^{-4}$
Bu	9.8	1.36	1.76	1.76
Re	40	150	150	150

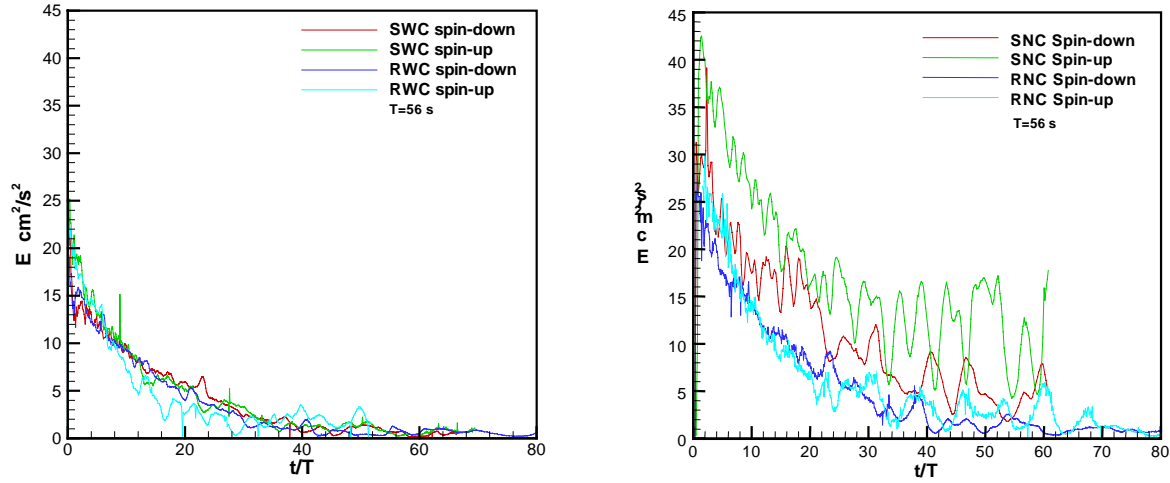
**Table 1. Dimensionless parameters.**

In the present experiments, we considered four different topographies: smooth (with/without canyon) and rough (with/without canyon). At least four experiments were conducted for each topographic arrangement differing in the forcing mechanism applied on the initial state of solid body rotation of linearly stratified ( $N=0.46 \text{ s}^{-1}$ ) fluid. The experiments included the following: flow produced by oscillatory forcing for two different sets of parameters ( $P_1$  and  $P_2$ , see Table 1), impulsively started upwelling-favorable flow ( $P_3$ ) and impulsively started downwelling-favorable flow ( $P_4$ ). The oscillatory forcing was introduced by modulating the turntable rotation rate and upwelling / downwelling favorable flow by decreasing/increasing impulsively the rate of rotation.

Flow characterization included measurement of Eulerian velocity fields by the CIV technique in horizontal planes at different depths, and monitoring of the evolution of density profiles by periodic shooting of seven density probes, distributed along two traverses; one stretching radially over the continental shelf and the other stretching over the slope and deep water. Velocity fields were typically obtained in rectangular areas having a size of 210 cm x 160 cm with the smallest resolved scale being 6.5 cm x 6.5 cm. In the experiments designed to characterize the turbulence, the field of view was smaller, 51 cm x 38 cm and the smallest resolvable scale was 1.6 cm x 1.6 cm.

During the collection of these new laboratory data sets, the SEOM and ROMS numerical models have been applied to retrospective simulations of the earlier data obtained at ASU (Perenne *et al.* 2001a, 2001b). Goals of these simulations include model/model comparative studies, and the development of post-processing diagnostics for application to these earlier laminar and the newly obtained turbulent data sets.

## RESULTS



**Figure 2: Evolution of the average kinetic energy for the impulsively started flows over different topographies: SWC - smooth with canyon, RWC - rough with canyon, SNC- smooth without canyon and RNC - rough without canyon.**

The research conducted during FY 01 was concentrated mostly on (i) the impact of boundary turbulence on evolution of the impulsively started flow, and (ii) impact of boundary turbulence on residual flows produced in the case of oscillatory forcing. Figure 2 shows the evolution of the kinetic energy, spatially averaged over the measurement area, for topography interrupted by a canyon (on the left) and continuous topography (on the right) for the cases of impulsively started flows (upwelling or downwelling favorable) over the topography with or without roughness elements. The contrast between smooth and rough cases, *i.e.*, turbulent versus laminar flows, is greatest in the case of continuous topography. The laminar and turbulent cases differ in the rate of decay of kinetic energy, as well as in evolution of the flow at later stages. In the case of smooth topography, large periodic eddy structures develop at later stages of flow evolution, and these eddies are more prominent in the case of downwelling favorable flows. In the case of rough topography, eddy structures are much smaller, less energetic, and mostly confined to the area of the shelf break. In the case of topography interrupted with a canyon, evolution of kinetic energy is less affected by the presence of the roughness elements, at least within the canyon where these velocity measurements are obtained. It would be interesting to analyze the evolution of the kinetic energy in an area situated away from the canyon in order to assess the effect of the canyon on the evolution of the basin flow.

Residual flows are obtained by averaging velocity fields over ten oscillating cycles. The residual flow pattern obtained for the smooth topography is consistent with results of laboratory experiments and numerical simulations obtained by Perenne et al. 2001a. The dominant flow features are a boundary current along the shelf and a cyclonic eddy close to the downstream wall, which is especially prominent at the level below the shelf break. Although the flow patterns are similar for the cases of the smooth and rough topographies, two differences are noticed: (i) the intensity of the residual circulation is stronger in the case of the smooth topography, and (ii) the boundary current along the shelf break is wider in the case of the smooth topography. The amplitude of the forcing velocity at the shelf break

was 5 cm/s in these experiments, and maxima of the downstream velocity components of the residual current are 2.5 cm/s and 1.8 cm/s for smooth and rough topographies, respectively.

Implementation and debugging of the ROMS canyon simulations began in July 2001, and the central calculation reported in Perenne *et al.* (2001b) has now been replicated. This exercise proved to be a valuable "learning exercise" for use of the rapidly evolving (and still rather untested) ROMS code. In particular, we have identified what appears to be a parallel bug in the north/south periodicity option (required to replicate the annular geometry), and weak instabilities in the rotated mixing tensors. Minor modifications of the experimental design were necessary to get ROMS to run. Interestingly, similar modifications were not required in SEOM. Lastly, we have successfully implemented a post-processing procedure for SEOM results that calculates a complete kinetic/potential energy budget balance for the numerical simulations. Given the large (in the numerical model) displacement of the isopycnal surfaces in these experiments, a KE/PE budget is likely to be a powerful interpretative tool for cross-shelf mixing and mean flow generation.

## **IMPACT/APPLICATION**

There is increasing interest, related to both military and civilian needs, in predictions of currents, temperature and salinity fields in the coastal zone. Meeting this goal will require the development of more reliable numerical models for the coastal zone. Owing to the fact that detailed measurements in space and time for testing coastal ocean models are often lacking, this project seeks to use carefully designed laboratory experiments, which include turbulence, to serve as data sources in the improvement of numerical models of the coastal zone.

## **TRANSITION**

As noted below, Dr. Haidvogel is developing a website of test problems for numerical ocean models. The results of the present experiments, as well as those for the laminar flows addressed earlier, will be placed on that website so that all interested numerical modelers will have easy access to the laboratory data.

## **RELATED PROJECTS**

Under separate funding from ONR, one of the PI's and his colleagues are developing a World Wide Web site containing a variety of analytic, quasi-analytic and geophysical test problems for ocean models. One of the geophysical test problems currently being formulated for deployment on the web site is the central laboratory experiment of Perenne *et al.* (2001b). As described above, we now have (or will shortly have) replicate simulations obtained with both SEOM and ROMS for this case.

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